

UNITED STATES AIR FORCE RESEARCH LABORATORY

BREATHING RESISTANCE PROPERTIES OF THE COMBAT ACE (TLSS PHASE IV B & C) CHEMICAL DEFENSE RESPIRATOR

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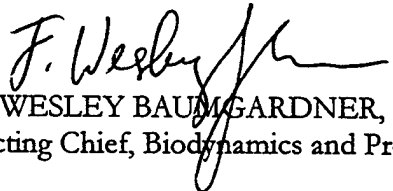
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BREATHING RESISTANCE PROPERTIES OF THE COMBAT ACE (TLSS PHASE IV B & C) OXYGEN SYSTEM

SUMMARY

Acceleration protection afforded by pressure breathing for G (PBG) was recently introduced when the COMBAT EDGE breathing system was retrofitted to F-15 and F-16 aircraft. In addition to providing PBG, the CRU-93 breathing regulator in this system has a lower breathing resistance compared to the CRU-73/A it replaces. Because it confers a measurable degree of G protection, preservation of this low resistance feature has remained a priority in hardening the system against chemical threats.

Chemical hardening of earlier aircraft oxygen systems produced undesirable increases in breathing resistance: The AERP (Aircrew Eye Respiratory Protection) system was developed by installing the then standard oxygen mask (MBU-12/P) in a chemically protective hood and routing inspired breathing gas through a C-2 filter canister attached to the mask hose. This report describes how COMBAT EDGE has been chemically hardened into COMBAT ACE by enclosing its new (MBU-20/P) pressure breathing mask in an improved protective hood, and integrating a new and lower resistance Low Profile Aircrew Filter Pack (LPAFP). The combination of this new filter, and the reduced breathing resistance CRU-93 regulator, gives the COMBAT ACE system a better breathing system performance than both the conventional oxygen system and NBC equipment (AERP) it replaces.

Although COMBAT ACE (TLSS Phase IV B & C) performed better than AERP in these tests, the filters in both systems raised breathing resistance levels above those normally found in the unhardened oxygen systems. Of the four systems examined, only the unhardened COMBAT EDGE meets ASCC (Air Standardization Coordinating Committee) Standard 61/22A over most of its performance range. Its integration into COMBAT ACE resulted in a loss of ASCC compliance, but test-subject questionnaires revealed no reports of air hunger or reduced acceleration protection. Similarly, others have shown that COMBAT ACE affords the same high-G endurance increases conferred by COMBAT EDGE. Thus, the resistance occasioned by adding an LPAFP filter element does not significantly compromise the system.

INTRODUCTION

In the mid-1980s an advanced development program known as the Tactical Life Support System (TLSS) sponsored the first-ever in-flight assessment of several emerging aircrew technologies (7): Greatly improved acceleration protection, achieved by pressure breathing for G (PBG), was supported by a low resistance (high flow capacity) breathing system, a digitally controlled anti-G valve, and an integrated garment which combined torso counter pressure provisions with an extended coverage lower G-suit. The same garment could be inflated on schedules providing an improved (60,000 ft) pressure breathing for altitude (PBA) capability. Compatible means of nuclear, biological, and chemical (NBC) protection were conferred by a choice of two different respirator concepts (addressing vapor only, and liquid threats respectively), and inclusion of a charcoal barrier in the integrated suit. Optional thermal conditioning was provided by a liquid cooled vest and airframe mounted vapor-cycle chiller. Breathing gas was supplied by an on-board oxygen generating system (OBOGS).

The system was flight tested in an F-15B at Air Force Flight Test Center, Edwards AFB, CA from November 1986 through January 1987 (5). At the same time, a variant incorporating a conventional liquid oxygen (LOX) source and a PBG-modified standard (CRU-73/A) breathing regulator was tested in the F-16 (4). Both programs were highly successful: The original TLSS concept was embraced by the Lockheed-Boeing team and emerged with little change as the life support system for the YF-22; its technologies have continued to mature as that aircraft progresses through engineering and manufacturing development (EMD). The F-16 variant described above has similarly evolved into COMBAT EDGE (COMBined Advanced Technology, Enhanced Design G Ensemble), a PBG retrofit program for F-15 and F-16 aircraft.

COMBAT EDGE entered service rapidly because it was able to capitalize on the engineering investment already present in existing equipment. The then standard CRU-73/A regulator was upgraded to become the CRU-93, with a selectable PBG capability, improved flow capacity, and reduced breathing resistance. The existing High Flow G-valve was modified to produce a linear and stabilized pressure schedule that could provide a more accurate and reliable enabling signal for the onset of PBG. The integrated TLSS garment was abandoned in favor of the traditional flight suit, over which was worn the conventional CSU-13B/P anti-G suit, and a new torso counter pressure garment (CSU-17/P) derived from the TLSS design. A new oxygen mask (MBU-20/P) and automatic-tensioning kit (KMU-511/P) were developed to configure the standard HGU-55/P helmet for PPG. The ensemble appears in Figure 1. Integrating compatible NBC gear was deferred pending maturation and acceptance of the ensemble's basic design.



Figure 1. The COMBAT EDGE flying ensemble. Shown are the new MBU-20/P pressure breathing mask, the CSU-17/P vest, and the CSU-13B/P anti-G trouser.

report describes the breathing characteristics of that system and compares them to earlier design specifications and appropriate ASCC (Air Standardization Coordinating Committee) Standards.

While COMBAT EDGE was in development, the AERP program was established to provide a standard aircrew respirator for NBC protection. Because PBG was experimental at the time, the AERP program chose to incorporate a (then) standard MBU-12/P oxygen mask. This mask is unable to contain the pressures required for PBG and its manifold lacks a connection for a counter pressure vest. Thus, the MBU-12/P mask cannot provide the acceleration protection afforded by PBG. Consequently, today's crewmembers are forced to choose between equipment providing acceleration protection without NBC protection (COMBAT EDGE), or an NBC capability with degraded acceleration protection (AERP).

Anticipating this incompatibility, we integrated the newer MBU-20/P mask into its own NBC respirator in a final modification to the original TLSS contract. By adding Phases IV B & C, the deliverables were expanded to include the detailed specification and brass board prototypes of a pressure-breathing respirator now called COMBAT ACE. This

METHODS

System Description

The COMBAT ACE breathing system is comprised of the CRU-93/A (COMBAT EDGE) oxygen regulator through which breathing gas flows to the aircrew via a Low Profile Aircrew Filter Pack (LPAFP), a distribution manifold, and an MBU-20/P mask inside the respirator cowl.

1) CRU-93/A Breathing Regulator:

The CRU-93/A is a pressure-demand, PBG-capable oxygen regulator designed and built by Litton Instruments & Life Support, Davenport IA. It is similar to the CRU-73/A it replaces, except for the addition of a proportioning valve that receives a sense line from the G-valve that controls the application of PBG. PPG onset begins at 4 G (3.5 psi G-valve pressure) and increases linearly at 12 mmHg/G (8 mmHg/psi) to a maximum of 60 mmHg at 9 G. Oxygen dilution and high altitude pressure breathing schedules are unchanged from those of the standard CRU-73/A. Automatic safety pressure nominally begins at 27,000 feet, followed by the onset of pressure breathing for altitude (PBA) at 39,000 feet; pressure then increases linearly to a maximum of 30 mmHg at 50,000 feet.

The control panel has normal lighting provisions, a pressure gauge, a flow indicator, a test port and three switches for selecting the desired operating mode: From right to left in Figure 1 these switches include: 1) A green On/Off switch with a double-action (pull and advance) position for PBG selection, 2) a white dilution switch for selecting 100% oxygen, or "Normal" (appropriately diluted) breathing gas, and 3) a red switch for selecting Emergency, Normal or Test Mask pressures. Except for the new double-action PBG selector, this switch array follows conventional layout and switch positioning of earlier regulators so that long taught emergency "gang loading" (all switches "up" with a hand-sweep) procedures remain valid in cases of suspected hypoxia.

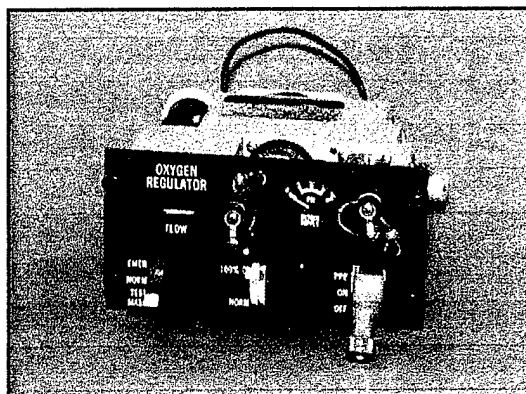


FIGURE 2. CRU-93/A Pressure Demand/PBG Oxygen Regulator. View of the control panel showing the three mode selection switches.

2) The Low-Profile Aircrew Filter Pack (LPAFP):

Breathing gas leaving the regulator flows via a standard hose and quick disconnect assembly to the Low-Profile Aircrew Filter Pack (LPAFP), designed and built by Racal Filter Technologies, Ltd. (Figure 2). The unit provides C-2 equivalent protection in a more compact and easily integrated design. Locating the hose connectors at opposite ends of the canister eliminates the need for two 90 degree hose fittings previously required to accommodate a C-2 filter in the AERP design. This innovation both reduces the assembly's

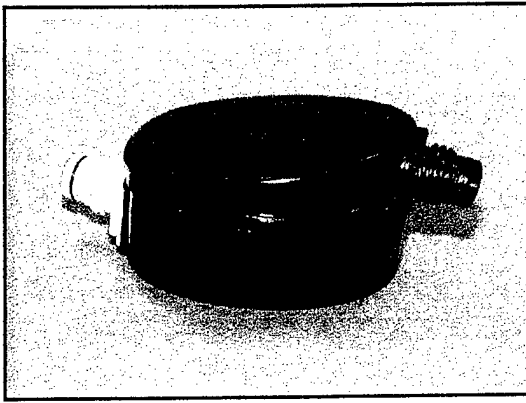


Figure 3. The Low Profile Aircrew Filter Pack (LPAFP). Fusiform shape does much to ease integration with other equipment, as well as reduce breathing resistance.

COMBAT EDGE CRU-94/P connector, frequently referred to as the ITB (Integrated Terminal Block). In the non-CD mode, it functions as a Y-connector, receiving breathing gas from the regulator and distributing it to the mask and counter pressure garment (vest) compartments. It also has a bayonet connector to receive the emergency oxygen supply. Given the optional nature of PBG, the vest connector is both self sealing and equipped with an overboard dump valve. The self-sealing feature allows the system to be safely used without a vest (in the non-PBG mode). The absent vest connector additionally exposes a 40 mmHg dump valve intended to vent excessive pressure should the PBG feature be inadvertently selected when the vest is not worn. This basic architecture is preserved in the COMBAT ACE manifold that features the addition of a parallel channel for delivery of filtered (visor demist) gas from an airframe-mounted or portable blower source. A selectable "cross-over" feature also diverts gas from the breathing circuit for visor demist use under conditions of blower failure, or in ground operations when a portable filter-blower supplies the breathing circuit. As with the ITB, the manifold attaches to the parachute harness using a standard wedge-plate connector.



Figure 4. The TLSS Phase 4 B & C (COMBAT ACE) respirator. Shown here with the HGU-55/P helmet.

overall height and significantly decreases breathing resistance. While the pressure drop across the internal filter element approximates that for the NATO C-2 canister, the faring and relocation of its fittings reduces the system's pressure drop to about half that seen in AERP (6). The LPAFP attaches via a short hose to the respirator manifold and is stabilized in its position by a tether attaching it to the parachute harness.

3) The Respirator Manifold:

The manifold assembly is adapted from the

4) The Phase 4B &C (COMBAT ACE) Respirator:

The respirator (Figure 4) consists of a bromobutyl rubber cowl which incorporates a COMBAT EDGE MBU-20/P oxygen mask, a clear polycarbonate visor with demist provisions, a neck dam, a drinking facility and communication connections. It can be worn under a standard HGU-55/P flight helmet and is manufactured in four sizes: small, medium, large, and extra-large. The mask receives filtered breathing gas from the CRU-93/A regulator via the LPAFP and respirator manifold. The visor compartment receives either blown filtered air from its own supply

circuit, or a back-up flow of breathing gas introduced by selection of the crossover feature on the manifold. Gas exit from the cowl space is controlled by a large dump valve assembly in the nape area.

Unmanned Testing

Breathing system performance may vary with the regulator's operating mode (i.e., selection of normal or safety pressure, dilution or 100% oxygen etc.) and eight different permutations of switch position are possible with the CRU-93/A. Therefore, we focused our investigation on the most commonly used settings. These were (left to right on the red, white and green switches in Figure 1): Normal/Normal/PBG and EMER/Normal/PBG respectively. The remaining possible switch configurations received unmanned assessment at ground level only and are not reported here.

A computer controlled Variable Profile Breathing Simulator (VPBS) mannequin, developed by Technology Incorporated (now Krug International), was used to characterize the breathing system's response to controlled and reproducible flow demands. The TLSS Phase 4C/D (COMBAT ACE) respirator together with an appropriately modified HGU-55/P helmet were mounted on the VPBS head-form. Putty was applied to the region of the mask seal to prevent leakage. A Fleish flowmeter was installed in the "throat" of the VPBS to measure inspiratory and expiratory flows. The respirator was connected in turn to its manifold, an LPAFP, and a CRU-93 regulator instrumented to provide information on its inlet (supply) and outlet (breathing) pressures. These instruments were calibrated in units of psi and in.Wg (inches water gauge) respectively. The respirator's drinking facility was modified to allow monitoring of mask pressure (mmHg) and oxygen concentration (%) using a Perkin Elmer mass spectrometer. Demist air flow was provided to the manifold by a separate filter-blower assembly.

Replicate tests were conducted at chamber altitudes of 22,000, 15,000 and 8,000 feet, and again at ground level. At each altitude, breathing profiles were manipulated to present a range of inspiratory peak flows ranging from 20 - 200 lpm at breathing rates of 8 - 50 breaths per minute (bpm). Higher breathing rates were necessarily associated with higher inspiratory flow values on the VPBS.

Manned Testing

Volunteer test subjects were briefed in accordance with AFI 40-402, rendered appropriate informed consent, and were subsequently trained in operation and use of the TLSS-Phase 4C/D (COMBAT ACE) breathing system. The CRU-93/A regulator was instrumented to provide information on its supply (inlet) pressure (psi), outlet pressure (in.Wg), and outlet flow (lpm). The respirator's drinking facility was modified to allow monitoring of mask pressure (mmHg) and sampling of respiratory gases (O₂ and CO₂ %) by a Perkin Elmer mass spectrometer. Subjects' expiratory flows were not measured because addition of a flowmeter circuit to the expiratory valve significantly distorted mask pressure measurements. A stationary bicycle ergometer was used to introduce measured activity and corresponding increases in respiratory demand. Each subject's cardiovascular response was monitored using a three lead electrocardiogram.

After an ear and sinus check, subjects were taken to a chamber altitude of 22,000 feet and monitored for 30 seconds under each of the following six conditions: 1) at rest, 2) at rest with speech, 3) light work cycling (60 watts), 4) light work with speech, 5) moderate work cycling (120 watts), and 6) moderate work with speech. Subjects were instructed to maintain 60 rpm pedal speed on the ergometer. A standardized speech passage was inserted at each activity level to shorten the period of inspiration and provoke higher inspiratory peak flows, simulating those which occur while executing an anti-G straining maneuver (AGSM). This same sequence was repeated at 15,000 feet, 8,000 feet, and again at ground level. Only one set of regulator switch settings was evaluated on a given flight. Immediately after the flight each subject completed a standardized questionnaire to assess perceived breathing ease or impairment. Twenty-six such questionnaires were collected.

RESULTS

Unmanned test data (Figure 4) depict the average expiratory (positive upper trace) and inspiratory (negative-going lower) pressure values as a function of imposed flow demands. Note that the inspiratory pressures required to sustain a given flow rate decrease with altitude. This tendency is true for both switch settings (NL/NL/PBG, and EMER/NL/PBG), but the negative-going pressure correlates are somewhat reduced in the latter (EMER or safety pressure) case.

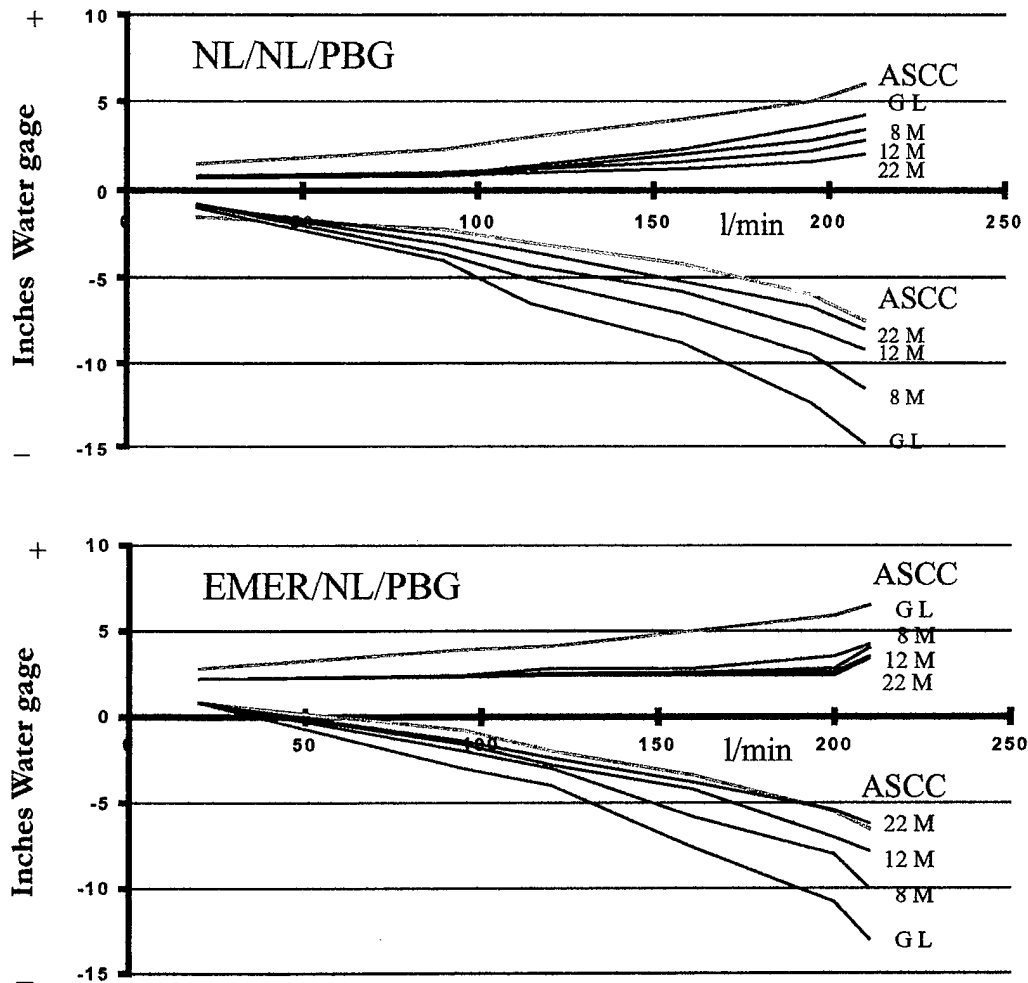


Figure 5. Pressure/flow relationships measured in unmanned tests of the COMBAT ACE breathing system. The families of curves represent the effects of increasing altitude on the different switch configurations identified.

Because of previously discussed experimental design considerations, manned test data could be collected for inspiratory resistance only. Analysis of the individual test cases produced a family of curves describing mean mask cavity pressure as a function of corresponding average peak flow values. These data are presented in Figure 6. The altitude effect is again evident; the pressure correlates of a given flow decrease at higher cabin altitudes. Again,

selection of the EMER (safety pressure) setting tends to raise the curves closer to ASCC standards.

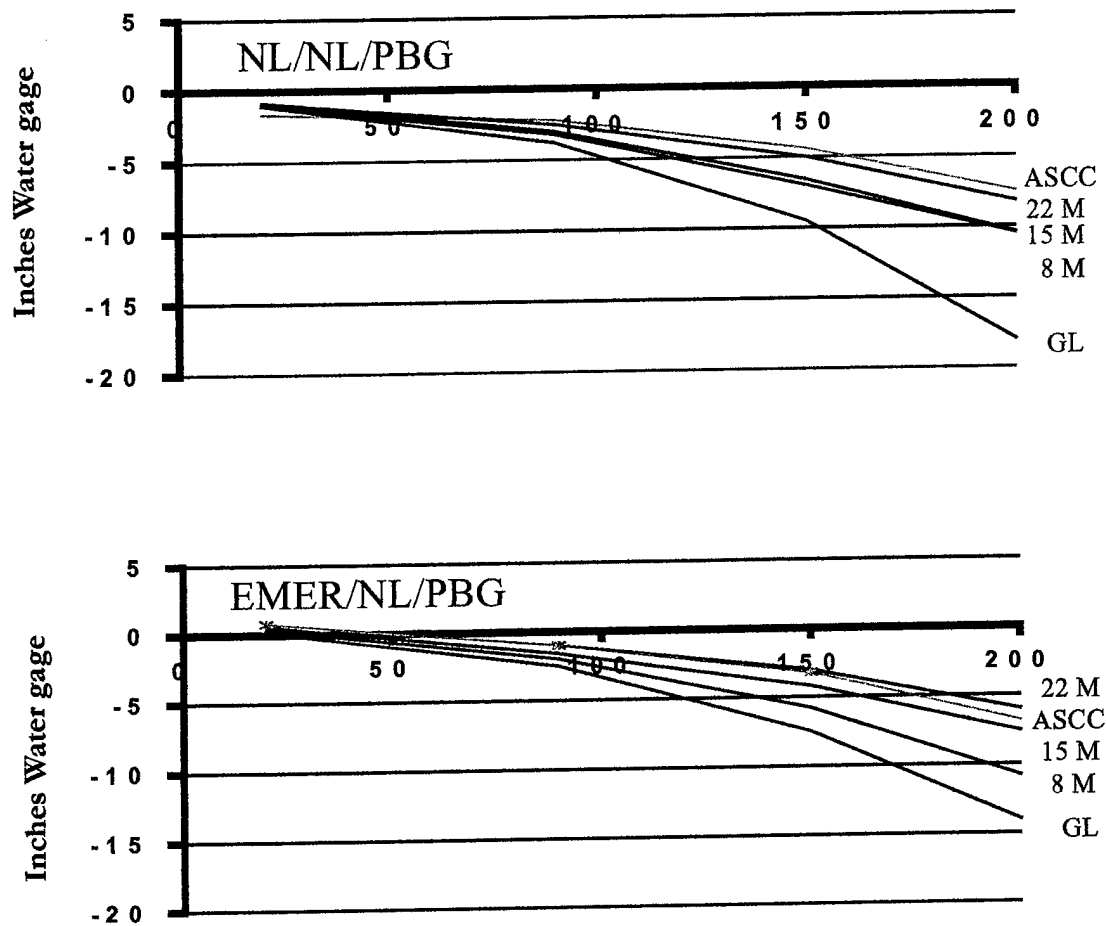


Figure 6. Inspiratory pressure/flow relationships evident in manned tests of the COMBAT ACE breathing system. Note that inspiratory resistance decreases with increasing altitude, and with selection of the EMER (safety pressure) option.

The acceptability of these resistances can be inferred from the participants' responses to a post-flight questionnaire. Eighty-one percent responded with less than a 25% perceived impairment in their ability to perform the work required, 12 percent with 25-50 percent impairment, and only 7 percent responded with 50-75 percent impairment. All, however, were able to satisfactorily complete the series of four repeated exercise profiles, at increasingly lower altitudes, each of which finished with moderate activity and superimposed speech. Reports of perceived breathing resistance varied greatly among the subjects, but tended to rise with ergometer workload, not the altitude influence noted above.

DISCUSSION

Over the years, there has been much interest in decreasing the resistance (increasing the flow capacity) of aircrew breathing systems, but little change in the specifications to which they are built. Justifying related engineering change has been difficult because existing standards appear to have worked quite well for decades, and the benefits of such an improvement are transparent during the relatively low demands of normal breathing. Their true value emerges primarily at high (and in aviation, frequently transient) levels of demand, and in circumstances requiring the added resistance of a chemical filter. In such cases, increased flow capacity attenuates otherwise large negative pressure excursions which can add to the work of breathing, promote inboard agent leakage, and compromise the acceleration protection afforded by positive pressure breathing for G (PBG).

In the 1980s, the need for NBC protection in tactical fighters arrived with such urgency that consideration of these subtleties was deferred. Emphasis instead focused on quickly hardening the existing oxygen system comprised of the (then) standard CRU-73/A regulator, a CRU-60/P quick-disconnect device, and an MBU-12/P oxygen mask. Although safe, adequate and state-of-the-art when it was introduced, it is currently unable to meet the pressure/flow requirements of more recent guidance (ASCC Air Std 61/22A). When this system was chemically hardened into AERP, by introducing a C-2 canister to the oxygen supply hose, and integrating the oxygen mask into an air-ventilated hood assembly, its breathing resistance increased further still (Figure 6). Reduced performance was accepted because filter-gained increases in resistance were a necessary part of hardening the system, and resulting pressure/flow characteristics (although poorer than the original system) were subjectively tolerable in manned tests. In sum, the performance decrement accepted for the sake of NBC protection was judged a reasonable tradeoff, and AERP went on to achieve levels of aircrew acceptance much higher than the interim mask (MBU-13/P smoke mask) it replaced.

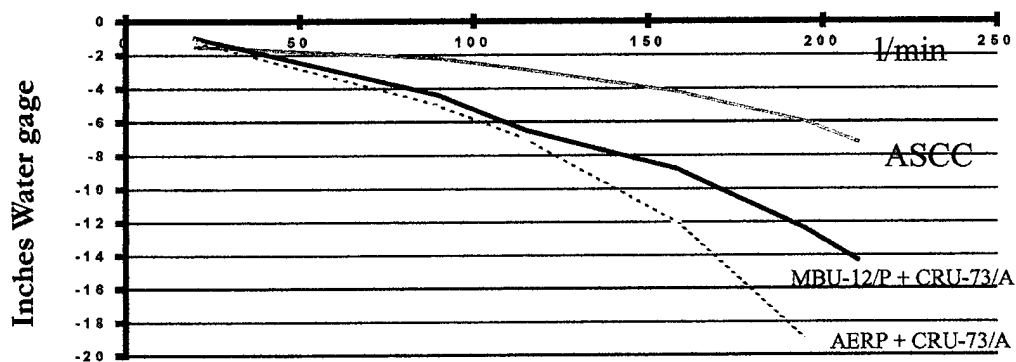


Figure 7. Comparison of the pressure/flow requirements expressed in ASCC Air Std 61/22A to those of the conventional (MBU-12/P based) system, and those of the chemically hardened AERP breathing system.

Introduction of COMBAT EDGE brought renewed interest in improvement. Aware that it would later become necessary to chemically harden that system, and that breathing resistance was detrimental to G-tolerance (6), developers from the outset specified an increased flow capacity for the system's CRU-93/A pressure breathing regulator. Other recognized

limitations of the AERP design including filter resistance, poor oxygen mask sealing properties, and the inability to interface with a counter pressure vest, were similarly addressed under a modification to the original TLSS contract (Phases 4 B and C). Together these efforts resulted in development of the COMBAT ACE (chemically hardened COMBAT EDGE) system described and evaluated in the present study.

A summary of pressure/flow findings for the Phase 4 B/C (COMBAT ACE) system appears in Figure 7. They are compared to the properties of the original (non-NBC) COMBAT EDGE breathing system, and the previously referenced requirements of ASCC Air Std 61/22A. Note that performance of the (unhardened) COMBAT EDGE system closely approximates Air Standard requirements. This performance reflects both previously mentioned efforts to increase responsiveness of the CRU-93 regulator, together with uniquely low breathing resistance properties of the MBU-20/P oxygen mask. Chemical hardening of the system into COMBAT ACE, by introducing the low-profile filter pack (LPAFP), an NBC manifold, and integrating the MBU-20/P mask into a chemically protective hood, produced the results in the lower curve. Although offering higher resistance than COMBAT EDGE alone, the COMBAT ACE values are at the same time noticeably better than those for AERP. Comparing Figures 6 and 7 reveals that wearing COMBAT ACE exerts 5 in. wg less respiratory effort (to achieve inspiratory peak flows on order of 190-200 l/min) than with AERP. Additionally, over the lower portion of its range, COMBAT ACE has better pressure/flow properties than the standard (non NBC) oxygen system (middle curve, Fig 6) recently replaced by COMBAT EDGE.

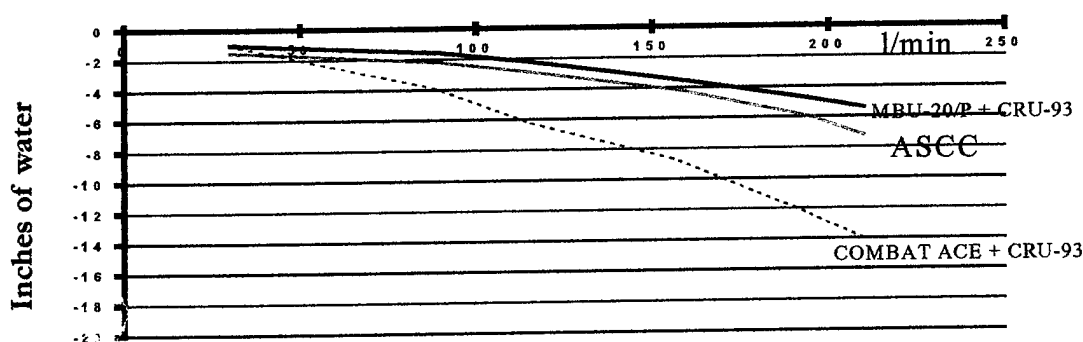


Figure 8. Comparison of the pressure/flow requirements expressed in ASCC Air Std 61/22A to those of the COMBAT EDGE system, and its chemically hardened version the TLSS Phase 4B/C (COMBAT ACE) respirator.

The fact that neither AERP nor COMBAT ACE meets the design guidance of ASCC Air Std 61/22A is attributable to more than previously discussed design rationale (resistance trade-offs for the protection of a filter). There is also a shortage of relevant guidance: Air Std 61/22A is actually intended for conventional (non-NBC) demand breathing systems, while a related standard for chemically protective hoods (ASCC Air Std 61-23) refers only to allowable mask pressure swings, not to their absolute value. Although both references were considered in setting desired design goals, neither is properly applicable to a system with an in-line filter, a design feature common to both of these systems. Notwithstanding the risks arising from such absent guidance, each system achieved levels of comfort and protection

superior to the equipment it replaced: The earlier MBU-13/P has been followed by the better AERP, which will be replaced in turn by a better COMBAT ACE.

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